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Article

Phthalic acid esters and polybrominated diphenyl occurrence in a coastal lagoon: Spatial patterns, trends and potential risk

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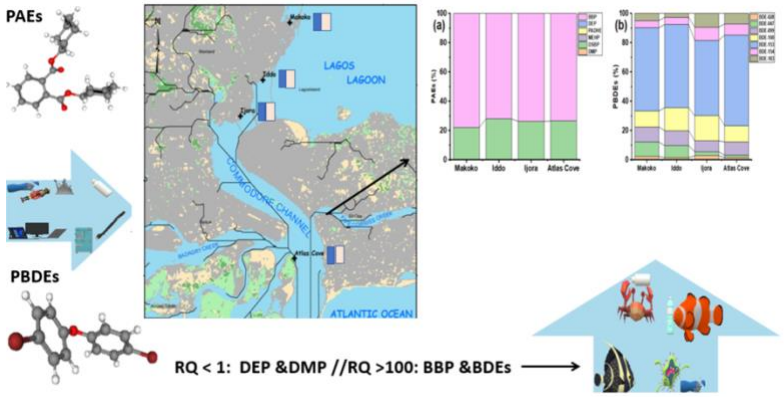

Highlights

- *Benzyl butyl phthalate and BDE-153 dominated detected PAEs/PBDE congeners*
- *Elevated contaminant levels particularly at Makoko and Atlas Cove indicates intense anthropogenic loading.*
- *High-risk profiles for key PAEs and PBDEs suggest the potential for adverse effects to algae and broader aquatic biota.*
- *The findings emphasis the need for effective regulatory action to curb emissions and safeguard ecosystem and public health.*

Abstract

Phthalate esters (PAEs) and polybrominated diphenyl ethers (PBDEs) are emerging contaminants whose bioaccumulative potential pose serious risks to ecosystems and human health. This study assessed the concentrations, distribution, and ecological risks of PAE and PBDE congeners in surface water and sediment from four selected catchments along the Lagos Lagoon, Nigeria. Extraction of target compounds was performed using liquid–liquid and ultrasonication techniques, followed by gas chromatography mass spectrometry (GC–MS) analysis. All examined PBDE congeners and two of the six targeted PAEs, di-sec-butyl phthalate (DSBP) and benzyl butyl phthalate (BBP) were detected in all sampling locations and matrices. In contrast, diethyl phthalate (DEP) and phthalic acid decyl hept-2-yl ester (PADHE) was detected in few sites. Mean concentrations of PAEs ranged from 0.39–0.52 mg/L in surface water and 0.33–0.57 mg/kg in sediment, while mean PBDE concentration ranged from 0.047–0.11 mg/L and 0.06–0.21 mg/kg in surface water and sediment, respectively. Benzyl butyl phthalate contributed 73.48% of total PAEs in surface water and 73.07% in sediment, whereas 2,2',4,4',5,5'-hexabromodiphenyl ether (BDE-153) accounted for 55.14% of total PBDEs in surface water and 34.75% in sediment. Principal component analysis

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(PCA) revealed a dominance of low molecular weight PAEs: dimethyl phthalate (DMP) and high-brominated PBDEs commonly linked to domestic effluents, urban runoff, plastic based materials, and consumer products indicating intense human activities especially at Makoko and Atlas Cove. Risk quotient (RQ) indicates low risk (RQ < 1) from DEP and DMP, whereas levels of BBP suggest the potential for significant ecological risk (RQ > 100), especially on algae in most locations. Detected PBDE concentrations with RQs ≥ 100, likely resulting from the debromination of heavily brominated deca-BDEs, suggest considerable risk to aquatic biota. Notably, the elevated levels of hexa- and hepta-BDE congeners at Makoko and Atlas Cove indicate potential adverse effects on aquatic organisms. These findings highlight the need for stringent regulatory measures and informed management actions, to safeguard Nigeria's coastal environments and public health.

1 Introduction

Emerging contaminants (ECs), or contaminants of emerging concern (CECs), encompass a diverse array of naturally occurring and synthetic substances including plastic additives that are increasingly recognized as a global environmental threat. Their widespread occurrence limited regulatory control, and inadequate monitoring have raised mounting concerns about their potential risks to both human health and ecosystem integrity (Wang et al., 2024). In 2020, the global plastic additives market was valued at $48.41 billion with projections to grow to $75.20 billion by 2028 at an annual rate of 5.7% (Fortune, 2022). Improper waste disposal has led to the accumulation of these additives in coastal ecosystems, with their leaching and release rates influenced by the type of plastic, chemical properties of the additives, and various environmental and anthropogenic factors (Gunaalan et al., 2020; Bridson et al., 2021). Among the most widely used additives, phthalic acid esters (PAEs) and brominated flame retardants (BFRs) are recognized as highly hazardous substances and endocrine disruptors (Mackintosh et al., 2004; Net et al., 2015; Maceira et al., 2019; Groh et al., 2019). The PAEs and polybrominated diphenyl ethers (PBDEs) are commonly incorporated in specific proportions in plastic production and processing to enhance polymer performance, functionality, and longevity (Adeogun et al., 2015; Hahladakis et al., 2018). However, their presence in various environmental compartments, including water, sediment, and biota, raises significant concerns about food chain contamination and biomagnification, ultimately impacting human health (Adeniyi et al., 2011; Chai et al., 2019).

Polybrominated diphenyl ethers, a class of recalcitrant, bioaccumulative halogenated compounds have emerged as significant environmental pollutants in recent times. The PBDEs represent the most widely produced group of BFRs. In recognition of their persistence and toxicity, PBDEs were listed as persistent organic pollutants (POPs) under the Stockholm Convention Treaty in 2009 (Stockholm Convention Clearing House, n.d.). Commercially, PBDEs are marketed in three technical mixtures: decabromodiphenyl ether (decaBDE), octabromodiphenyl ether (octaBDE), and pentabromodiphenyl ether (pentaBDE). The penta- and octa-products consist of several brominated diphenyl (BDE) congeners, while the deca-product is composed entirely of BDE-209 (Hu et al., 2010). Due to environmental and health concerns, the European Union banned the production and use of both pentaBDE and octaBDE in 2004 (De Boer, 2009). The PBDEs are introduced into the aquatic environment through a variety of sources, including direct and indirect discharges from urban domestic and industrial sewage, as well as atmospheric deposition. Additional sources include municipal waste streams containing paints, plastics, textiles, furniture, and electronic equipment, as well as runoff from effluents and agricultural chemicals (Barnhoorn et al., 2004; Scholz and Mayer, 2008; Grieshaber et al., 2018; Carmalin and Lima, 2018). In contrast, PAEs are widely used synthetic organic compounds that have been in commercial use since the 1930s, owing to their increasing economic and industrial relevance (Heo et al., 2020). Global production of PAEs is estimated at 6 to 8 million tons annually, with over 3 million tons consumed across various industries (Zhang et al., 2016; Seyoum and Pradhan, 2019). The PAEs are structurally characterized as dialkyl or alkyl/aryl esters of 1,2-benzene dicarboxylic acid (Annamalai and Vasudevan, 2020) and are typically grouped into high and low molecular weight compounds. Each group has distinct chemical and physical properties that define their respective applications (Katsikantami et al., 2016; Wang et al., 2019). High molecular weight PAEs, such as di(2-ethylhexyl) phthalate (DEHP) and butyl benzyl phthalate (BBP), are primarily used as plasticizers to improve the flexibility, durability, and transparency of plastic materials (Wormuth et al., 2006).

Recent studies have highlighted the fate, transport, and ecological risks of plastic additives and leachate (mixtures of additives) in the environment (Hermabessiere et al., 2017; Hahladakis et al., 2018; Groh et al., 2019; Gunaalan et al., 2020; Bridson et al., 2021). In Nigeria, coastal and lagoon ecosystems are increasingly threatened by rapid urbanization, industrialization, population growth, and

inadequate waste management infrastructure (Adewuyi and Adeleye, 2013). The Lagos Lagoon, a shallow brackish water environment is bounded in the north by several large rivers namely Ogun, Yewa, Ona, and Osun rivers as well as tidal creeks (Adeyi et al., 2017). During the period of rainfall, the lagoon empties in the south and opens into the Atlantic Ocean through the Lagos harbor (Alani et al., 2013; Adeogun et al., 2015). In addition to supporting livelihoods, recreation, and dense coastal settlements, the lagoon also receives domestic wastes and industrial effluents from the 80–85% of Nigeria's industries clustered around its catchment (Adeyi et al., 2017). Adewuyi and Adeleye (2013) documented the presence of 2,4,4'-tribromodiphenyl ether (BDE-28), 2,2',4,4',5,5'-hexabromodiphenyl ether (BDE-153), 2,2',4,4',5,6'-hexabromodiphenyl ether (BDE-154) and 2,2′,3,3′,4,4′,5,6′-octabromodiphenyl ether (BDE 205) in sediment samples during a baseline study. Adeyi et al. (2017) reported PBDE concentration in sediment and fish samples along the major discharge points and the tributary of the Lagos Lagoon, highlighting potential bioaccumulation risks. Oladejo et al. (2022) reported potential endocrine disruption, neurotoxicity, thyroid hormonal problems, brain malfunction, and other long-term health impacts on humans and animals due to the release of industrial effluents containing PBDEs into the Lagos Lagoon. Similarly, Adeogun et al. (2015) reported high concentration of DEHP, diethyl phthalate (DEP) and dibutyl phthalate (DBP) with predominance of DBP in fish and prawn from Epe and Lagos Lagoon. Fagbemi et al. (2024) observed high potential for carcinogenic risk from BBP and DEHP when used for bathing and drinking purposes.

Despite the documented evidence of the occurrence, increasing levels, and potential toxicity of plastic pollutants (Obiakara-Amaechi et al., 2025), and other pollutants of priority concern (Usese et al., 2020), in various environmental compartments in Lagos Lagoon, comprehensive assessment of both PAEs and PBDEs particularly the congeners remain understudied. The proximity of the water bodies to solid waste dump sites exposes nearby coastal communities to the chemicals present in the waste with the lagoon acting as a sink thereby amplifying the potential health risks and environmental consequences. In addition, the studies assessing the predictive risks of PAEs and PBDEs to aquatic biota in the Lagos Lagoon remain scarce. Therefore, this study investigated 6 PAE compounds; dimethyl phthalate (DMP), di-sec-butyl phthalate (DSBP), phthalic acid, decyl hept-2-yl ester (PADHE), diethyl phthalate (DEP), benzyl butyl phthalate (BBP), mono(2-ethylhexyl) phthalate (MEHP) and 2,4,4'-tribromodiphenyl ether (BDE-028), 2,2',4,4'-tetrabromodiphenyl ether (BDE-047) and 7 PBDE congeners namely, 2,2',4,4',6-pentabromodiphenyl ether (BDE-100), 2,2',4,4',5-pentabromodiphenyl ether (BDE-099), 2,2',4,4',5,6'-hexabromodiphenyl ether (BDE-154), 2,2',4,4',5,5'-Hexabromodiphenyl ether (BDE-153), and 2,2',3,4,4',5',6-heptabromodiphenyl ether (BDE-183) in surface water and sediments from the Lagos Lagoon.

This study aimed to provide evidence-based data on the potential ecological risk of PAEs and PBDEs, with emphasis on contaminants posing the greatest threats to algae, crustaceans, fish, and the broader ecosystem. We hypothesized the presence of relatively higher levels of PAE and PBDE, particularly near the industrial discharge sites and e-waste runoff, with high molecular weight PAEs (BBP) and key PBDE congeners (BDE-47, and BDE-99) dominating due to their widespread use in plastics and electronics.

2 Materials and methods

2.1 Study area and sample collection

A total of 12 surface water samples and 12 sediment samples were collected from four sites, Makoko, Iddo, Ijora, and Atlas Cove on the Lagos Lagoon, Nigeria (**Fig. 1**). Sampling was conducted monthly from September to November 2023, capturing peak-rainfall conditions and maximum runoff into the lagoon (Daniel and Ibrahim, 2024). Water samples were collected at a depth of 0–15 cm using 2.5 L Winchester glass bottles with screw lid. The bottle was pre-cleaned by rinsing with water from the sampling location on three separate occasions at the point of collection (Fagbemi et al., 2024). Sediment samples were collected with stainless-steel van Veen grab at approximately 80 cm depth (Olarinmoye et al., 2020). After collection, sediment samples were wrapped in self-sealing aluminum foil, already precleaned with acetone to ensure preservation and prevent contamination, transported in a cooler with ice chest to the Department of Chemistry Environmental Laboratory, University of Lagos for storage at -20°C prior to analysis.

2.2 Physicochemical characteristics of surface water and sediments

Parameters including temperature, turbidity, electrical conductivity (EC), salinity, pH, and dissolved oxygen (DO) were measured in situ using U-52 multi-parameter water checker (Horriba Ltd., Kyoto, Japan). Sediment samples were analyzed for parameters such as pH, EC, and total organic content (TOC). To determine pH and EC in the sediment samples, 10 g of each sample contained in a 50 mL beaker was mixed with 100 mL of deionized water. The

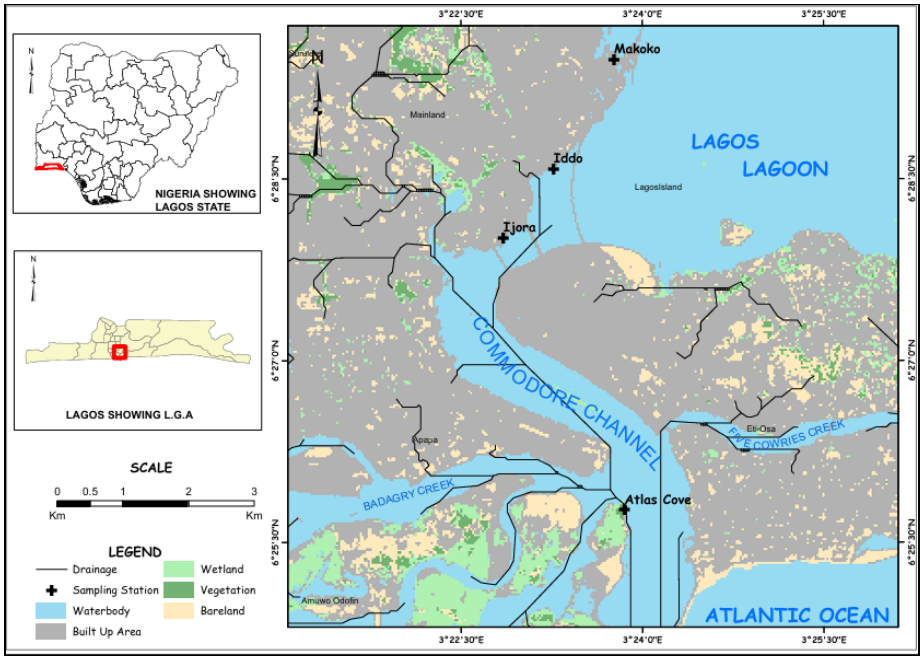

Figure 1. *Map showing sampling sites on the Lagos Lagoon, Nigeria.*

mixture was stirred, allowed to settle, and the electrodes of a multifunctional pH/EC meter (Calibrated Axiom PHS-25) were immersed to measure the respective parameters, following the method outlined by Okoro et al. (2024). The TOC was determined using Walkley and Black wet oxidation method (Walkley and Black, 1934).

2.3 Pretreatment of PAEs and PBDEs in surface water and sediments

One liter of surface water was filtered via pre-combusted (450 °C for 4 h) glass fiber filters (GF/F, 0.7-mm pore size, Whatman) and stored in precleaned amber glass bottles (1 L) to eliminate particulate matter prior to extraction according to Liu et al. (2014). Bottles were pre-cleaned by rinsing sequentially with hot water, tap water, distilled water, and acetone before being oven dried. For sediment sample, 100 g was mixed with anhydrous sodium sulfate until it flowed freely before extraction.

2.4 Extraction of PAEs and PBDEs in surface water and sediment

Following pretreatment, the surface water and sediment samples were split into two aliquots for targeted extraction and analysis of PAEs and PBDEs. For surface water, 250 mL of each representative sample was transferred into a pre-cleaned separatory funnel and acidified to pH < 2 using concentrated sulfuric acid (H_2SO_4, analytical grade). Sediment samples (30 g each) were placed in pre-cleaned glass centrifuge tubes and mixed with an equal volume of organic-free reagent water, which was prepared by pre-extracting ultrapure water with methylene chloride to remove trace organics. Sodium hydroxide (1 M NaOH) was added as needed to neutralize acidic extracts prior to cleanup.

The PAEs and PBDEs were extracted from surface water using liquid–liquid extraction (LLE) with 30 mL portions of methylene chloride (DCM; HPLC grade), repeated three times. Sediment samples were extracted using ultrasonication with methylene chloride (30 mL), repeated three times. For both matrices, the combined extracts were passed through a column of anhydrous sodium sulfate to remove residual water, and the solvent was concentrated to 1 mL using a Kuderna-Danish (K.D) concentrator prior to gas chromatography–mass spectrometry (GC–MS) analysis. All extractions were performed in duplicate to ensure reproducibility (USEPA, 1984; Olutona et al., 2016; Kingsley and Witthayawirasak, 2020; Dueñas-Moreno et al., 2024).

2.5 Instrumental analysis of PAEs and PBDEs

The total concentration of 6 PAE compounds: dimethyl phthalate (DMP), di-sec-butyl phthalate (DSBP), phthalic acid, decyl hept-2-yl ester (PADHE), diethyl phthalate (DEP), benzyl butyl phthalate (BBP) and mono(2-ethylhexyl) phthalate (MEHP), and 7 PBDE congeners namely 2,4,4'-tribromodiphenyl ether (BDE-028), 2,2',4,4'-tetrabromodiphenyl ether (BDE-047), 2,2',4,4',6-pentabromodiphenyl ether (BDE-100), 2,2',4,4',5-

pentabromodiphenyl ether (BDE-099), 2,2',4,4',5,6'-hexabromodiphenyl ether (BDE-154), 2,2',4,4',5,5'-hexabromodiphenyl ether (BDE-153), and 2,2',3,4,4',5',6-heptabromodiphenyl ether (BDE-183) were determined using mix standard of PAE and PBDE congeners from AccuStandard for the instrumental calibration.

Identification and quantification of the six PAEs and seven PBDE congeners were carried out using GC–MS following procedure specified by EPA Method 8270 (USEPA, 1984). The procedure reported by Deng et al. (2021) guided compound selection and confirmation ions while instrumental conditions were optimized for an Agilent 7820A gas chromatograph coupled to 5975C inert mass spectrometer (with triple axis detector) operating in scan and sim mode with electron-impact source (Agilent Technologies). A DB-5 capillary column coated with 5% Phenyl Methyl Siloxane (30 m length x 0.32 mm diameter x 0.25 µm film thickness) (Agilent Technologies) was employed for separation of stationary phase of PBDE and PAE compounds with optimized conditions maintained in the gas chromatograph. The carrier gas, helium was used at a constant flow of 2.0161 mL/min at an initial nominal pressure of 9.5729 psi and an average velocity of 54.028 cm/sec for PBDEs while 1.5 mL/min at an initial nominal pressure of 1.5603 psi and an average velocity of 44.411 cm/sec was utilized for PAEs. After that, 2 µL and 1 µL of respective samples of PBDEs and PAEs were injected in spitless mode at an injection temperature of 300°C. This was followed by purge flow to split vent at (50 mL/min at 2 min with a total flow of 52.565 mL/min) and (30 mL/min at 0.35 min with a total flow of 31.936 mL/min) for PBDEs and PAEs in that order, with gas saver mode switched off. The oven was initially programmed for PBDEs at 150°C for (1 min), ramped at 17°C/min to 315°C (5 min) with run time of 15.706 min and a 5 min solvent delay. For PAEs, oven was initially programmed at 40°C for (1 min) and then ramped sequentially at 15°C/min to 100°C (3 min), 20°C/min to 240°C (5 min) and 10°C/min to 310°C (8 min) with total run time of 35 min and a 5-minute solvent delay. The mass spectrometer used for the determination of PAE and PBDE compounds were operated in electron-impact ionization mode at 70eV with an ion source temperature of 230°C, quadrupole temperature of 150°C, and transfer line temperature of 280°C. Acquisition of ion was via scan mode (scanning from m/z 45 to 550 amu at 2.0s/scan rate).

2.6 Quality control

All glassware including volumetric flask employed in the laboratory procedure were treated with chromic acid, washed with soap, and rinsed sequentially with hot water, tap water, distilled water, and acetone before being oven-dried (Ramzi et al., 2018). Prior to analysis, the mass spectrometer (MS) was auto tuned with perfluorotributylamine (PFTBA) to optimize the sensitivity of the compounds being analyzed by recording the current of the following quantifier ions: m/z 69, 219, and 502 for all the PAEs and PBDEs.

2.7 Ecological risk assessment for PAEs and PBDE congeners

The risk quotient (RQ) was used to assess the potential ecological risk according to the European Commission's Technical Guidance Document (EC, 2003). Assessment of RQ on target PAEs was estimated as the quotient of the measured environmental concentration (MEC) in water or sediment sample and the predicted no-effect concentration (PNEC). RQ values for PAEs are determined for three trophic levels which include fish, invertebrates, and algae/cyanobacteria using their toxicity data collated from USEPA Ecotoxicology database (USEPA, 2012) and relevant literature (Li et al., 2017; Liu et al., 2021) are presented in **Table 1**.

$$RQ = MEC / PNEC_{Water/Sediment}$$

$PNEC_{water}$ was further calculated as a fraction of the toxicologically relevant concentration –No observed effect concentration (NOEC) or 50% Effective concentration (EC) of the specific species and standard assessment factor (AF) as follows:

$$PNEC_{water} = NOEC \text{ or } EC_{50} / AF$$

While for sediment it is depicted below:

$$PNEC_{sediment} = KSPM\text{-}water \times PNEC_{water} \times 1000 / RHOSPM$$

Where $PNEC_{water}$ is the predicted no-effect concentration of PAEs in surface water, $PNEC_{sediment}$ is the predicted no-effect concentration of PAEs in sediment, KSPM-water (L/L) is the suspended particulate matter (SPM)–water partitioning coefficient, and RHOSPM is the bulk density (1,150 g/L) for suspended particulate matter.

For PBDEs, assessment of ecological risk in the surface water and sediment samples was computed via RQs on non-target organisms dwelling in water column and benthos, respectively, according to their acceptable quality guidelines set by the Federal Sediment Quality Guidelines (FSeQGs) (Environment Canada, 2013). The PBDEs congeners technical formulation are tri-(BDE-28), tetra-(BDE-47), penta-(BDE-99, -100), hexa-(BDE-153, -154) and hepta-BDE

Table 1. *PAEs toxicity data of sensitive aquatic organism.*

PAEs group	Taxonomic group	Species	Toxicity data (µg/L)	AF	$PNEC_w$ (µg/L)	$PNEC_s$ (µg/kg)	References
DMP	Algae	*Pseudokirchneriella subcapitata*	96 h, population NOEC = 10,000	10	1,000	1.33	Li et al. (2017)
	Crustaceans	*Daphnia magna*	21 d, mortality, NOEC = 9,600	10	960	1.28	Li et al. (2017)
	Fish	*Oncorhynchus mykiss*	102 d, mortality NOEC = 11,000	10	1,100	1.47	Li et al. (2017)
DEP	Algae	*Pseudokirchneriella subcapitata*	96 h, population NOEC = 8,106	10	810.8	2.51	Li et al. (2017)
	Crustaceans	*Americamysis bahia*	21 d, mortality, NOEC = 2,700	10	270	0.84	Li et al. (2017)
	Fish	*Lepomis macrochirus*	28 d, morphological, NOEC = 8,106	10	165	0.51	Li et al. (2017)
BBP	Algae	*Pseudokirchneriella subcapitata*	96 h, population, NOEC = 60	100	0.3	1.2	Liu et al. (2021)
	Crustaceans	*Daphnia magna*	21 d, mortality NOEC = 280	1,000	3.7	5.6	Liu et al. (2021)
	Fish	*Oncorhynchus mykiss*	96 h, population, EC50 = 820	1,000	1.7	0.82	Liu et al. (2021)

Note: $PNEC_w$ = $PNEC_{water}$, $PNEC_s$ = $PNEC_{sediment}$, and AF = Assessment factor.

(BDE-183) (Chai et al., 2019). For sediment, the FSeQG standard concentrations were normalized to organic content (OC) for tri-, tetra-, penta-, hexa- and deca-BDE congeners are 44, 39, 0.4, 440, and 19 ng/g in that order, while the acceptable levels of tri-BDE, tetraBDE, penta-BDE, hexa-BDE, and hepta-BDE in water are 46, 24, 0.2, 120, and 17 ng/L respectively (Shao et al., 2018). The calculated RQ values is expressed in the equation below:

$$RQ = Ci/Csi$$

Where, RQ is the risk quotient of PBDE in surface water or sediment, Ci is the measured concentration of PBDE in surface water or sediment, Csi is the standard acceptable concentration according to FseQGs.

A RQ < 0.01 indicates a low ecological risk, values between 0.01 and 1 denote a medium risk, and RQ > 1 signifies a high ecological risk (Ramzi et al., 2020).

2.8 Data analysis

Descriptive statistics (mean and standard deviation) were computed using MS Excel, while data visualization including principal component analysis (PCA) were carried out using Origin pro-2018 software. In computing percentage congener composition, PCA was used to determine the potential sources of PAEs and PBDEs and estimating ecological risk assessment in across sampling locations. Concentrations below the limit of detection (LOD) were substituted with LOD/2 as appropriate (Liu et al., 2018). Concentrations were shown as mg/kg dry weight (dw) for sediment samples, and mg/L for water samples. The percentage distribution of PAEs and PBDEs was calculated across all sampling locations. The LOD for PAEs and PBDEs in surface water is 0.00001 mg/L while in sediment is 0.00001 mg/kg.

3 Results and discussion

3.1 Physicochemical parameters of surface water and sediment

The results of the physicochemical properties in twelve surface water and twelve sediment samples, which provide insight into the characteristics and conditions of the environmental matrix during the study, are presented in

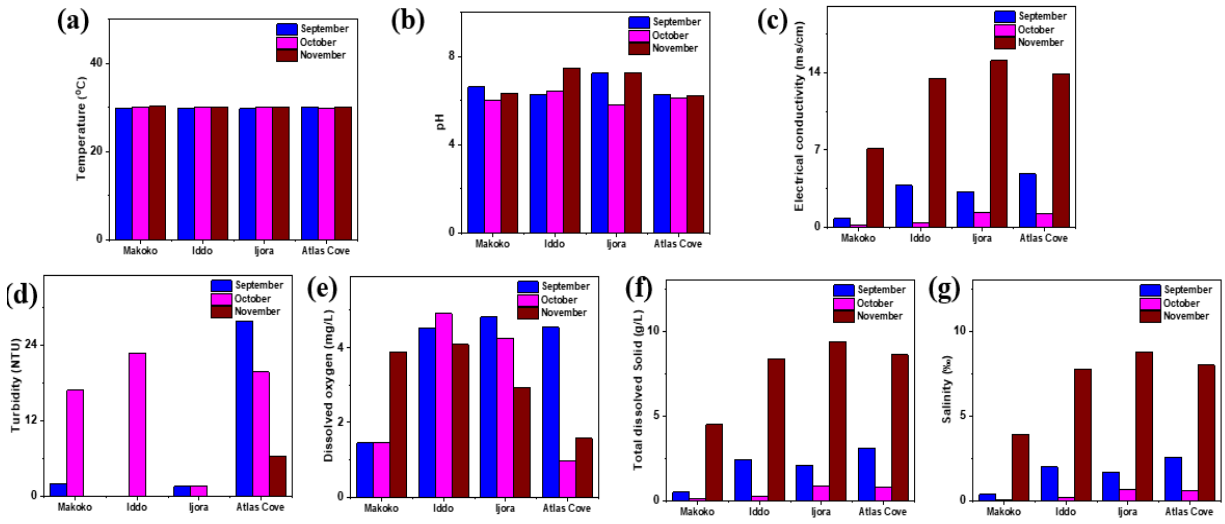

Figure 2. *Spatiotemporal variations in surface water: (a) temperature, (b) pH, (c) electrical conductivity, (d) turbidity, (e) dissolved oxygen, (f) total dissolved solid, and (g) salinity across the sampling locations.*

Figures 2 & 3. Surface water temperature ranged from 29.78°C (Ijora) to 30.18°C at Makoko. The DO was relatively low at Atlas Cove when compared to Makoko, Iddo, and Ijora sites. Across all stations, DO was mostly less than 5 mg/L except at Makoko, where a mean concentration of 5.06 mg/L was recorded in October. Previous investigation suggests DO between 4–9 mg/L are essential for marine organisms including fishes (Abdus-Salam et al., 2010). The low DO and hypoxic condition (0.97 mg/L) at Atlas Cove indicate stressed condition attributed to high level of organic waste (Coffin et al., 2018). Moreover, the site driven primarily by oil and gas activities serves as a major hub for receiving and distribution of imported fuel in Lagos.

The pH plays an important role in regulating metabolic functions involving enzymes, hormones, and protein synthesis (Oyeleke et al., 2019). The obtained pH values were generally near neutral across all stations except for the slightly acidic pH value of 5.8, reported at Ijora. This may be attributed to input from industrial and domestic effluents. However, the average pH of 6.73 ± 0.66 and 6.76 ± 0.84 reported at Iddo and Ijora, respectively, fall within the recommended range of 6.5–8.5 according to the World Health Organization (WHO).

The highest and lowest salinity were recorded at Ijora (8.76‰) and Makoko (0.07‰) for November and October, respectively. The mean concentration of EC followed an increasing order of Makoko < Iddo < Ijora < Atlas Cove, with the highest value recorded at Atlas Cove. Electrical conductivity ranged from 0.14 mS/cm at Makoko to 15.10 mS/cm at Ijora, with an overall mean of 5.43 mS/cm. The observed variations in EC reflect differences in salinity, which indicate the degree of mixing between saline Atlantic Ocean water and freshwater inflows from terrestrial sources along the catchment (Adedayo et al., 2012). Since Atlas Cove is geographically closer to the ocean than Makoko, it experiences a stronger influence of saline water intrusion. Generally, the EC values of an aquatic system reflect its ability to conduct electricity, with lower salinity corresponding to lower conductivity (Oyeleke et al., 2019). Variations in these physico-chemical characteristics often correlate with changes in suspended particle matter and water clarity.

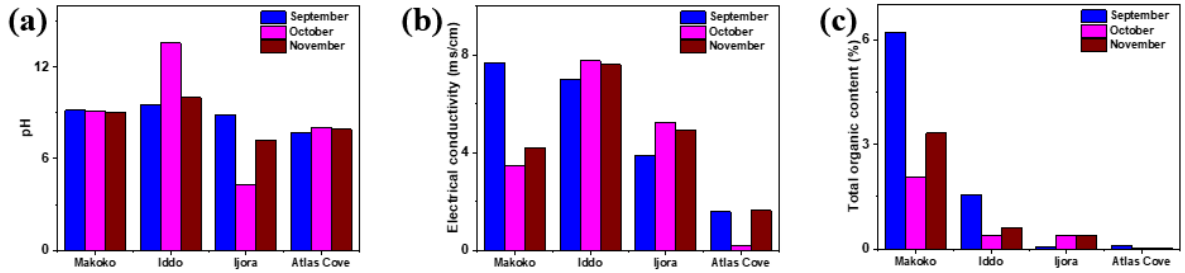

Figure 3. *Spatiotemporal variations in sediment: (a) pH, (b) electrical conductivity, and (c) total organic content across the sampling locations.*

The observed turbidity (NTU) was as high as 27.8 NTU at Atlas Cove in September and as low of 0.92 NTU at Iddo in December. The average concentration of turbidity for the sampled period increased gradually from Makoko to Iddo before a drastic drop at Ijora, recorded as 1.03 NTU. The turbidity measured at Ijora were consistently within acceptable limit of 5 NTU for upstream as recommended by the WHO. Contrarily, highest average turbidity of 17.9 ± 10.86 NTU recorded at Atlas Cove is linked to sand dredging, high shipping traffic and potential release of organic matter from oil and gas activities. Total Dissolve Solids (TDS) was as high as 9.36 g/L at Ijora in September and as low as 0.08 g/L at Makoko in October. The TDS concentration observed at most stations with the highest at Atlas cove were above the 500 mg/L (0.5 g/L) threshold established by the USEPA for optimal fish culture. High TDS suggest closeness to the sea (Emmanuel and Chukwu, 2018).

Sediment pH has a major impact on microbial activity, chemical speciation, and nutrient availability, and it significantly regulates ecosystem dynamics (Ighalo et al., 2022; Omuku et al., 2022). Atlas Cove and Ijora have strongly acidic and basic pH of 4.3 and 13, respectively, obtained in October. The values reported are not within the acceptable range of 6.5–8.5 recommended by the WHO. Slightly alkaline condition in most stations indicate the presence of carbonates ion in the surface water (Murhekar, 2011). The EC values were as low as 0.18 mS/cm at Atlas Cove and as high as 7.68 mS/cm recorded at Makoko for September and October, respectively. It can be noted that highest EC values reported for Makoko suggest loads of dissolved ion likely due to increasing domestic discharges and runoff. This agrees with low concentration reported by Obiakara-Amaechi et al. (2025), because of non-point sources of waste from anthropogenic activities. Fluctuations in salinity, pollution status and presence of chemicals that influences EC values can also result in its alteration (Marandi et al., 2013). Furthermore, variation in pH and EC can have profound impact on nutrient availability, dissolution of contaminant, and ecological health of the sediments (Okoro et al., 2024). The TOC values ranged from 0.03–6.21%, with an overall mean of 1.38%. The lowest values for TOC were recorded in October while the highest value was obtained in September. The increase in average TOC was recorded as Makoko > Iddo > Ijora > Atlas Cove. The generally low TOC suggest strong dilution effects from tidal influx. Total organic carbon and sediment texture are critical in determining the fate and source attribution of hydrophobic organic contaminants (Chai et al., 2019).

3.2 Spatial distribution of PAEs and PBDEs in surface water

The analysis of surface water samples collected from Makoko, Atlas Cove, Ijora, and Iddo on the Lagos Lagoon revealed the occurrence and spatial variability of PAEs and PBDEs, as summarized in **Table 2 and Figure 4**. The mean concentrations of PAEs in surface water exhibited spatial variability, with the highest concentrations observed at Makoko (0.52 ± 0.97 mg/L), followed by Atlas Cove (0.45 ± 0.87 mg/L), Iddo (0.42 ± 0.72 mg/L), and Ijora (0.39 ± 0.72 mg/L). These values represent 29.20%, 25.20%, 23.66%, and 21.94% of the cumulative ΣPAEs concentration at Makoko, Atlas cove, Iddo and Ijora, respectively (**Fig. 4a**). The concentrations observed in this study were lower than the reported range 1.88 ± 0.16 g/L to 15.74 ± 0.33 g/ L in Asunle stream (Fagbemi et al., 2024) but higher than the recorded value of 0.11 ± 0.01mg/L to 0.18±0.01 mg/L and 0.09 ±

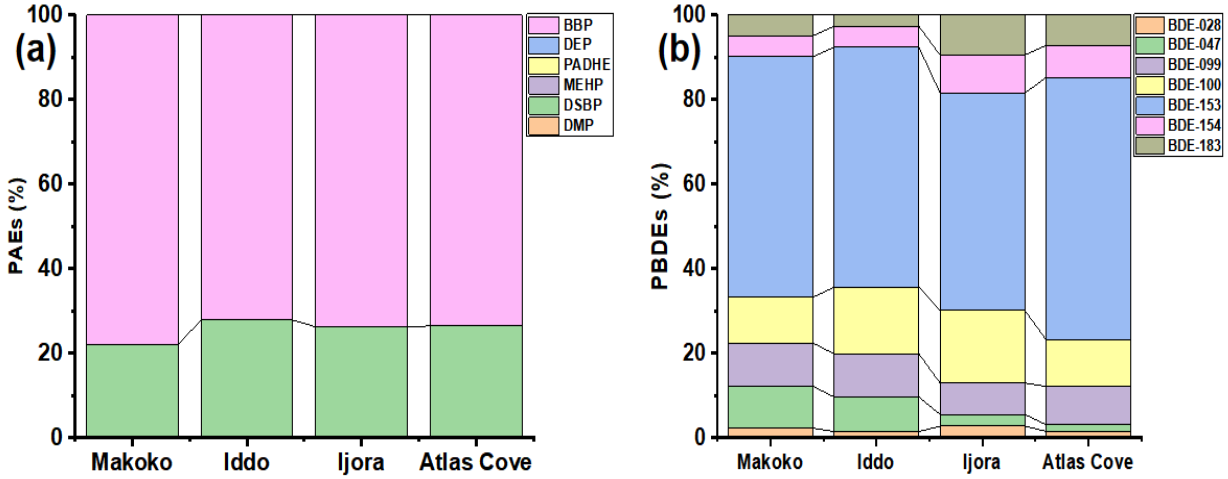

Figure 4. *Concentration of: (a) PAEs, and (b) PBDEs in surface water from selected locations during the study period.*

Table 2. *Mean ± standard error and percentage distribution of PAEs and PBDEs concentrations in surface water of the study area.*

Analytes		Sampling locations				Previous studies in Nigeria
		Makoko	Iddo	Ijora	Atlas Cove	
PAEs (mg/L)	DMP	BDL	BDL	ND	ND	BDL–0.01412 mg/L in Asunle Stream (Fagbemi et al., 2024)
	DSBP	0.70±0.004	0.71±0.004	0.71±0.01	0.72±0.02	NA
	MEHP	BDL	BDL	BDL	BDL	NA
	PADHE	BDL	BDL	BDL	BDL	NA
	DEP	BDL	BDL	BDL	0.70±1.21	0.11±0.01 mg/L in Epe Lagoon and 0.09±0.01 mg/L in Lagos Lagoon (Adeogun et al., 2015)
	BBP	2.45±0.94	1.84±0.45	1.99±1.28	1.99±1.28	BDL–0.00469 mg/L in Asunle Stream (Fagbemi et al., 2024)
	Mean PAEs	0.52±0.97	0.42±0.72	0.39±0.72	0.45±0.87	
	Total (%)	29.20	23.66	21.94	25.20	
PBDEs (mg/L)	BDE-028	0.01±0.01	0.01±0.001	0.009±0.002	0.01±0.01	$1.9x10^{-9}$–$4.4x10^{-9}$ mg/L in Lagos Lagoon (Oladejo et al., 2022)
	BDE-047	0.04±0.03	0.03±0.03	0.02±0.01	0.05±0.04	$0.3 x10^{-9}$–$2.4 x10^{-9}$ mg/L in Lagos Lagoon (Oladejo et al., 2022)
	BDE-100	0.04±0.03	0.06±0.06	0.06±0.05	0.08±0.09	$0.3 x10^{-9}$–$1.5 x10^{-9}$ mg/L in Lagos Lagoon (Oladejo et al., 2022)
	BDE-099	0.04±0.02	0.06±0.06	0.02±0.02	0.07±0.04	$0.7 x10^{-9}$–$2.7 x10^{-9}$ mg/L in Lagos Lagoon (Oladejo et al., 2022)
	BDE-154	0.02±0.03	0.03±0.01	0.03±0.03	0.06±0.05	ND–0.11 mg/L in Osun River (Adegunwa et al., 2024)
	BDE-153	0.68±0.32	0.16±0.11	0.17±0.1	0.46±0.49	ND–0.13 mg/L in Osun River (Adegunwa et al., 2024)
	BDE-183	0.01±0.001	0.03±0.02	0.03±0.01	0.05±0.05	ND in Osun River (Adegunwa et al., 2024)
	Mean PBDEs	0.06±0.06	0.05±0.05	0.047 ±0.047	0.11±0.11	
	Total (%)	21.06	20.82	17.65	40.40	

Note: BDL = Below Detection Limit, ND = Not Detected, Limit of Detection (LOD) = 0.00001 mg/L, and NA = Not Available.

0.01mg/L to 0.13 ± 0.01 mg/L in Epe and Lagos Lagoon, respectively (Adeogun et al., 2015). The high concentration of PAEs particularly at Makoko is due to leaching from unrestricted and disposal of plastic-containing waste suggesting localized pollution sources and urban run-off.

Among the six PAE congeners screened in the water samples, DMP was not detected at Ijora and Atlas Cove. However, all other PAEs were found at varying concentrations across the study sites. DMP, MEHP, PADHE, and diethyl phthalate (DEP) were either below detection limits or only marginally detected. Butyl benzyl phthalate constituted the highest proportion of detected PAEs, contributing 73.48% to the overall concentration across all study sites (**Fig. 4a**). Similar findings have been reported by Adeniyi et al. (2011) in the Ogun River catchment and Edjere et al. (2016) in the Ethiope River, where DMP was either undetected or found in negligible amounts in water due to restricted industrial use. The BBP may be attributed to point and non-point discharges of BBP-laden industrial and domestic effluents, where BBP serves as a plasticizer in polyurethane, polysulfide, and acrylic-based materials (Cao, 2010).

Spatial distribution of PBDE concentrations in surface water also varied across sites. The highest mean concentration was recorded at Atlas Cove (0.11 ± 0.11 mg/L), representing 40.40% of total PBDEs whereas the lowest was observed at Ijora (0.047 ± 0.047 mg/L) corresponding to 17.65%. Intermediate concentrations of

0.06 ± 0.06 mg/L were detected at Makoko, contributing 21.06% of the total, whereas Iddo contributed 20.82% (**Table 2**). The measured concentrations exceed the European Commission's safety threshold of 0.0002 mg/L. In contrast, previous studies reported lower levels; for instance, Oladejo et al. (2022) documented concentrations ranging from 8.0 × 10^{-10} to 1.26 × 10^{-8} mg/L in surface waters of the Gulf of Guinea, while Umulor et al. (2018) found values between 0.01 ± 0.003 and 0.02 ± 0.005 mg/L in Ologe Lagoon. High concentration especially at Atlas Cove could indicate pollution levels from urban and river runoff as well as atmospheric deposition. In terms of abundance, BDE-153 emerged as the most prevalent congener, constituting 55.14% of the total PBDE burden, followed by BDE-100 (13.24%) and BDE-099 (10.42%) (**Fig. 4b**). Minor contributions were observed from BDE-154 and BDE-183, accounting for 14.28%. BDE-047 and BDE-028 were the least abundant, contributing 5.01% and 1.91%, respectively. This agrees with Olutona et al. (2016) reported BDE-153 as the most prevalent PBDE in the Asunle stream.

3.3 Spatial distribution of PAEs and PBDEs in sediment

The concentrations of PAEs and PBDEs in sediment samples from Lagos Lagoon exhibited notable spatial variability (**Table 3** and **Figure 5**). Among the six targeted PAE congeners, concentrations ranged from not detected, particularly for DMP at Makoko and Iddo, to a maximum contribution of 73.06% of total PAEs for BBP (**Fig. 5a**). Four congeners, DMP, DEP, MEHP, and PADHE were generally below detection limits across most sampling locations, except for Makoko. At this site, PADHE was detected at a concentration of 0.007 mg/kg, contributing 0.06% to the total PAE burden. Low-molecular-weight PAEs (DMP and DEP) have shown to be more susceptible to microbial degradation of alkyl sidechain and removal from sediment when compared to high-molecular-weight congeners such as BBP and DEHP (Amir et al., 2005). Similar findings have been reported by Edjere et al. (2016) in the Ethiope River, where DMP was either undetected or found in negligible amounts due to restricted industrial use. The relatively high octanol-water partition coefficient (K_{ow}) of BBP enhances its lipophilicity and environmental persistence (Gao and Wen, 2016), which likely contributes to its prevalence in sediment.

Mean concentrations of PAE varied between 0.33 mg/kg at Atlas Cove and 0.57 mg/kg at Ijora, representing 18.21% and 31.60%, respectively, of the total PAE load across the lagoon (**Table 3**). Approximately 50.18% of total PAEs were recorded in Makoko and Iddo, with individual site mean concentrations of 0.42 mg/kg and 0.48 mg/kg, respectively. This result is within the range of concentrations (0.09 ± 0.02 mg/kg – 14.27 ± 1.76 mg/kg) in Asunle stream reported by Fagbemi et al. (2024). While Adeogun et al. (2015) reported lower concentrations (0.18 ± 0.01 – 0.3 ± 0.03 mg/kg) in Epe Lagoon and 0.14 ± 0.01 – 0.19 ± 0.01 mg/kg in Lagos Lagoon. The high concentrations at Makoko highlight the significance of comprehensive monitoring and targeted measures on the levels of PAEs.

For PBDEs, seven congeners were detected with BDE-153 emerging as the dominant compound across all sediment samples except at Makoko. The order of prevalence of PBDE congeners based on total abundance was as follows: BDE-153 (34.74%) > BDE-047 (34.54%) > BDE-099 (9.32%) > BDE-154 (7.73%) > BDE-100 (7.56%) > BDE-183 (4.54%) > BDE-028 (1.57%) (**Fig. 5b**). This aligns with the report by Adewuyi and Adeleye (2013) on co-dominance of BDE-153

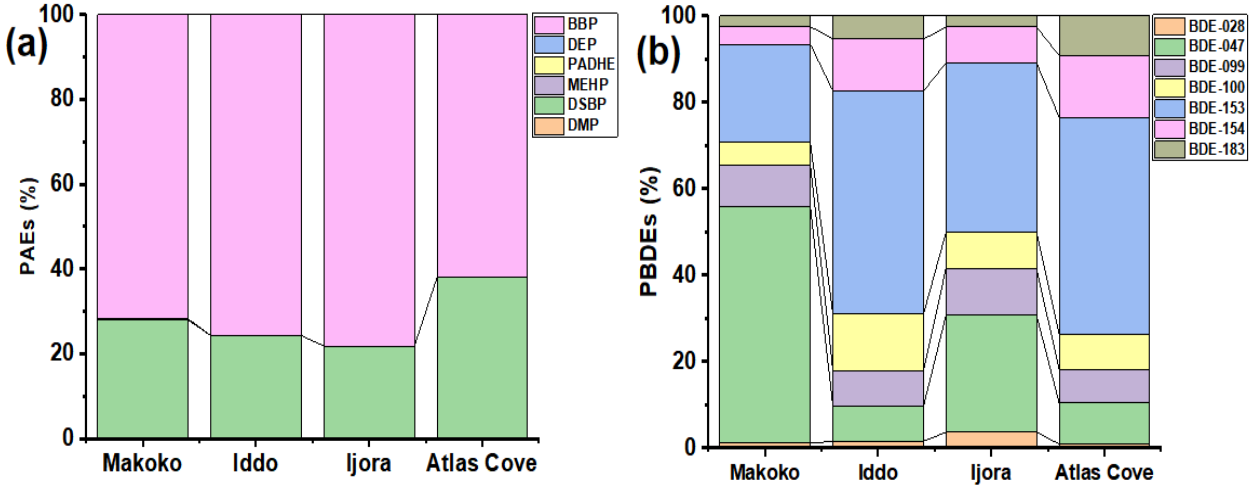

Figure 5. *Concentration of: (a) PAEs, and (b) PBDEs in sediment from selected locations during the study period.*

Table 3. *Mean ± standard error and percentage distribution of PAEs and PBDEs concentrations in sediment of the study area.*

Analytes		Sampling locations				Previous studies in Nigeria
		Makoko	Iddo	Ijora	Atlas Cove	
PAE (mg/kg)	DMP	ND	ND	BDL	BDL	BDL–0.19 mg/kg in Asunle Stream (Fagbemi et al., 2024)
	DSBP	0.70±0.01	0.70±0.01	0.74±0.08	0.74±0.09	NA
	MEHP	BDL	BDL	BDL	BDL	NA
	PADHE	0.007±0.01	BDL	BDL	BDL	NA
	DEP	BDL	BDL	BDL	BDL	0.3±0.03 mg/kg in Epe Lagoon and 0.19±0.01 mg/kg in Lagos Lagoon (Adeogun et al., 2015); BDL–0.21 mg/kg in Asunle Stream (Fagbemi et al., 2024)
	BBP	1.79±0.96	2.20±1.31	2.66±1.91	1.21±0.36	0.10–17.35 mg/kg in Asunle Stream (Fagbemi et al., 2024)
	Mean PAEs	0.42±0.76	0.48±0.95	0.57±1.20	0.33±0.51	
	Total (%)	23.23	26.95	31.60	18.21	
PBDEs (mg/kg)	BDE-028	0.02±0.01	0.01±0.01	0.02±0.01	0.004±0.004	0.70–10.36 mg/kg in Lagos Lagoon (Adewuyi and Adeleye, 2013); 0.09–0.13 mg/kg in Osun River (Adegunwa et al., 2024)
	BDE-047	0.79±0.42	0.04±0.03	0.14±0.1	0.04±0.04	0.11–0.14 mg/kg in Osun River (Adegunwa et al., 2024)
	BDE-100	0.07±0.04	0.07±0.07	0.04±0.02	0.04±0.03	0.09–0.41 mg/kg in Osun River (Adegunwa et al., 2024)
	BDE-099	0.14±0.02	0.04±0.01	0.06±0.01	0.03±0.03	0.13–0.19 mg/kg in Osun River (Adegunwa et al., 2024)
	BDE-154	0.06±0.05	0.06±0.02	0.04±0.03	0.06±0.06	0.22–16.66 mg/kg in Lagos Lagoon (Adewuyi and Adeleye, 2013); 0.10–0.14 mg/kg in Osun River (Adegunwa et al., 2024)
	BDE-153	0.33±0.27	0.27±0.03	0.20±0.07	0.22±0.19	0.22–16.66 mg/kg in Lagos Lagoon (Adewuyi and Adeleye, 2013); 0.14–0.21 mg/kg in Osun River (Adegunwa et al., 2024)
	BDE-183	0.04±0.03	0.03±0.03	0.01±0.01	0.04±0.05	0.10–0.14 mg/kg in Osun River (Adegunwa et al., 2024)
	Mean PBDEs	0.21±0.21	0.07±0.07	0.08±0.08	0.06±0.06	
	Total (%)	49.32	18.00	17.81	14.86	

Note: BDL = Below Detection Limit, ND = Not Detected, Limit of Detection (LOD) = 0.00001 mg/kg, and NA = Not Available.

and BDE-047. On the contrary, Oladejo et al. (2022) found BDE-028 to be the most abundant in sediment (37.5%) within the Lagos Lagoon. Elevated levels of BDE-153 and BDE-047 in sediment suggest debromination and wide usage of pentaBDE and octaBDE commercial products (Wang et al., 2015).

The mean PBDE concentration was highest at Makoko (0.21 ± 0.21 mg/kg) and lowest at Atlas Cove (0.06 ± 0.06 mg/kg) representing 49.32% and 14.86% of total, respectively (**Table 3**). A combined contribution of 35.81% of mean total with site-specific concentrations of 0.07 ± 0.07 and 0.08 ± 0.08 mg/kg was reported at Iddo and Ijora, indicating potential point sources and localized enrichment. The present result is within the range of concentrations from 0.05 ± 0.006 to 0.09 ± 0.006 ng/g reported for Ologe Lagoon (Umulor et al., 2018) and 0.11 to 23.33 mg/kg previously reported in Lagos Lagoon (Adewuyi and Adeleye, 2013).

Despite the variation across stations, measured concentration alongside previous studies on PBDEs in Lagos Lagoon were below Environment Canada's safe limit (6.124 mg/kg), suggesting low potential ecological risk from plastic-based materials. These results indicate the heterogeneous distribution of PAEs and PBDEs in Lagos Lagoon and highlight potential site-specific inputs and local pollution sources.

3.4 Potential source of PAEs and PBDEs in Lagos Lagoon ecosystem

The PCA retained two major components across both environmental matrices for PAEs and PBDEs having eigen values greater than 1 (**Figs. 6 & 7**). The PAE concentrations in surface water revealed two major components, accounting for 99.5% of total variance explained. PC1 included DMP, MEHP, BBP and PADHE, accounted for 90.9% of the total variance, with predominance of DMP and BBP. These compounds originated from Makoko (**Fig. 6a**). Similarly, PCA of six PAEs in surface sediments explained 91.5% of the total variance (PC1: 60.9%, PC2: 30.6%) (**Fig. 6b**). The PC1 was dominated by DMP and DSBP, with Atlas Cove showing the highest association, suggesting inputs from industrial additives, port activities, or maritime operations and plastic degradation products from urban run-offs and river inputs like Five cowries creek, Badagry creek and Commodore channel. The PC2 was primarily influenced by BBP, notably at Iddo, indicating urban runoff and consumer product sources. Makoko exhibited a site-specific contribution of PADHE, reflecting intense local human activity. Overall, the results indicate distinct sources and spatial variability of PAEs linked to domestic effluents, industrial inputs, localized anthropogenic activities and urban run-off.

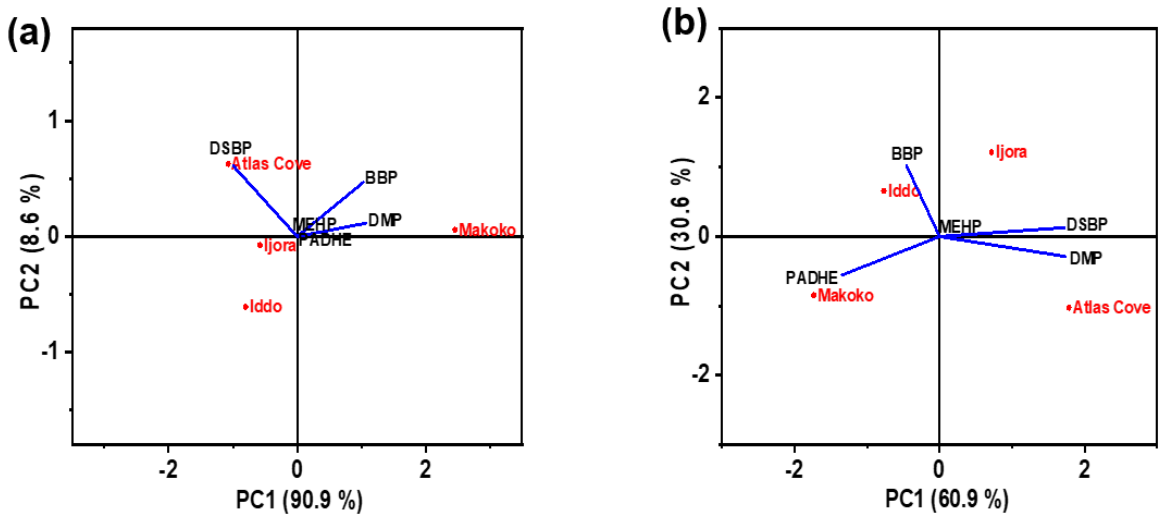

Figure 6. *Principle component analysis of PAE congeners in rotated two component space of two principal components source patterns: (a) surface water, and (b) sediment of the study area.*

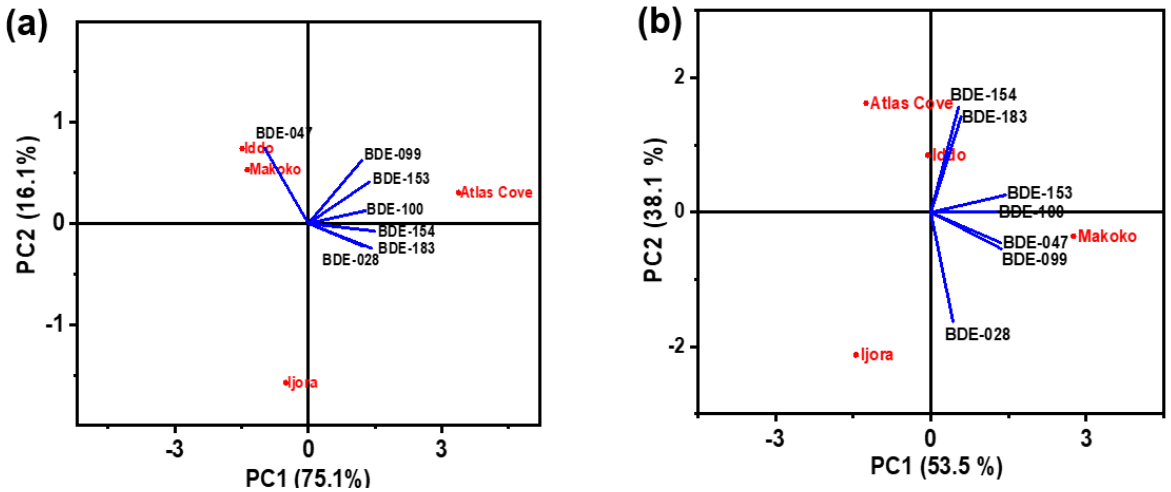

Figure 7. *Principle component analysis of PBDE congeners in rotated two component space of two principal components source patterns: (a) surface water, and (b) sediment of the study area.*

The PCA of PBDEs in surface water identified two main components explaining 91.2% of the variance. The PC1 (75.1%) was dominated by BDE-099, BDE-153, BDE-100, BDE-154, BDE-028, and BDE-183, indicating a common source from Atlas Cove (**Fig. 7a**). Higher-brominated congeners, primarily from octaBDE and decaBDE commercial mixtures, were likely introduced via atmospheric deposition and combined point and non-point sources (Oladejo et al., 2022). The PC2 (16.1%) was driven by BDE-047, reflecting the influence of lower-brominated penta-BDE congeners from widespread consumer product use at Iddo and Makoko. The PCA of seven PBDE homologues in surface sediment explained a total variance of 91.6% with PC1 showing 53.5% while PC2 accounted for 38.1% (**Fig. 7b**). The PC1 was predominantly influenced by all PBDE homologues with higher contributions observed at Makoko, suggesting possible inputs from landfill leachates and accumulation of electronic waste run-off ascribed to urbanization which directly translates to increased industrial activities (Oladejo et al., 2022).

3.5 Ecological risk of PAEs and PBDEs in Lagos Lagoon

Ecological risk assessment of PAEs and PBDEs revealed site- and compound-specific threats to aquatic biota. Risk quotients for individual and combined PAEs across four ecologically distinct sites are summarized in **Table 4**, while PBDE RQs in surface water and sediment are shown in **Figure 8**. For PAEs, RQ values in water samples were generally low (RQ < 1) except for BBP, which posed high risk (RQ > 100) to algae, crustaceans, and fish. DMP and DEP showed negligible risk across sites. Risk from sediment followed the order, BBP > DEP > DMP, with BBP on algae at Iddo reaching 5.9 × 10^3, whereas elevated BBP-risks on crustaceans (8.1 × 10^2) and fish (5.5 × 10^3) were observed at Ijora. In contrast, Okoro et al. (2024) reported negligible risk from BBP with values ranging from 5.632 × 10^{-4} to 5.632 × 10^{-4} in sediment samples from Ilorin metropolis, North Central Nigeria. Similarly, significant ecological risk from BBP in surface water at Makoko on algae, crustaceans and fish were 1.13 × 10^4, 9.17 × 10^2 and 2.0 × 10^3, respectively. These values were in several orders of magnitude higher than the reported values in surface water of Atoyac River, Central Mexico (Dueñas-Moreno et al., 2024). The cumulative maximum ecological risk (RQ_{mix}) in surface water on algae, crustaceans and fish were consistently 3.34 times higher than individual RQs while combined PAE effects in sediment dwelling organisms (RQ_{mix}) were 2 to 3 orders of magnitude higher than individual RQs, highlighting potential synergistic toxicity as prolonged PAE exposure may impact non-target species due to their pseudo-persistence (Long, 2006). PBDEs exhibited consistently very high RQs (≥ 100) in surface water and sediments, with hepta-BDE at Atlas Cove and hexa-BDE at Makoko posing the greatest risks (**Fig. 8**). These findings indicate significant ecological threats and potential bioaccumulation affecting secondary consumers. Similar high-risk PBDE profiles were reported in Buffalo River estuary, South Africa (Olaniyan et al., 2024), whereas Jiaozhou Bay and Chinese mangrove wetlands showed low to moderate risk (Chai et al., 2019; Fu et al., 2023). Overall, PAEs and PBDEs collectively represent a substantial ecological hazard to the aquatic ecosystem of the study area.

Given the ecosystem services provided by the Lagos Lagoon, including fisheries, transportation, recreation and tourism, these findings highlighted the urgent need for stringent regulatory action for PAEs and PBDEs in Nigeria. The implementation of restrictions and comprehensive monitoring frameworks, as adopted in other jurisdictions, is

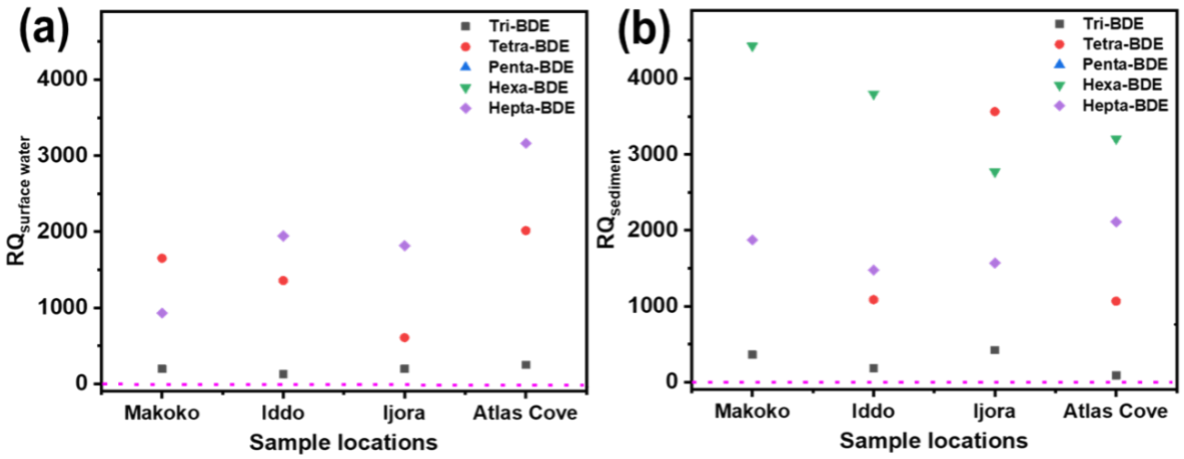

Figure 8. *Comparative evaluation of risk quotients (RQ) of PBDE congeners: (a) surface water, and (b) sediment of the study area.*

Table 4. *Estimated risk quotients (RQ) for individual and combined PAEs in surface water and sediment samples of the study area.*

Station	PAEs/RQ_{mix}	Aquatic biota	RQ_{mean} (Water)	RQ_{max} (Water)	RQ_{mean} (Sediment)	RQ_{max} (Sediment)
Makoko	DMP	Algae	5.0×10^{-6}	5.0×10^{-6}	NA	NA
		Crustaceans	5.2×10^{-6}	5.2×10^{-6}	NA	NA
		Fish	4.55×10^{-6}	4.55×10^{-6}	NA	NA
	DEP	Algae	6.2×10^{-6}	5.0×10^{-6}	6.7×10^{-4}	2.0×10^{-3}
		Crustaceans	1.85×10^{-5}	1.85×10^{-5}	2.0×10^{-3}	6.0×10^{-3}
		Fish	3.0×10^{-5}	3.0×10^{-5}	3.30×10^{-3}	9.8×10^{-3}
	BBP	Algae	8.12×10^{3}	1.13×10^{4}	1.5×10^{3}	2.1×10^{3}
		Crustaceans	6.61×10^{2}	9.17×10^{2}	3.2×10^{2}	4.38×10^{2}
		Fish	1.44×10^{3}	2.0×10^{3}	2.2×10^{3}	3.0×10^{3}
Iddo	DMP	Algae	5.0×10^{-6}	5.0×10^{-6}	NA	NA
		Crustaceans	5.2×10^{-6}	5.2×10^{-6}	NA	NA
		Fish	1.52×10^{-6}	1.52×10^{-6}	NA	NA
	DEP	Algae	4.55×10^{-6}	6.2×10^{-6}	6.7×10^{-4}	2.0×10^{-3}
		Crustaceans	1.85×10^{-5}	1.9×10^{-5}	2.0×10^{-3}	6.0×10^{-3}
		Fish	3.0×10^{-5}	3.0×10^{-5}	3.3×10^{-3}	9.8×10^{-3}
	BBP	Algae	5.5×10^{3}	8.5×10^{3}	1.83×10^{3}	5.9×10^{3}
		Crustaceans	4.5×10^{2}	6.9×10^{2}	3.92×10^{2}	5.38×10^{2}
		Fish	9.7×10^{1}	1.5×10^{3}	3.68×10^{3}	3.67×10^{3}
Ijora	DMP	Algae	NA	NA	3.8×10^{-3}	3.8×10^{-3}
		Crustaceans	NA	NA	3.9×10^{-3}	3.9×10^{-3}
		Fish	NA	NA	3.4×10^{-3}	3.4×10^{-3}
	DEP	Algae	6.2×10^{-6}	5.0×10^{-6}	2.0×10^{-3}	2.0×10^{-3}
		Crustaceans	1.85×10^{-5}	1.85×10^{-5}	6.0×10^{-3}	6.0×10^{-3}
		Fish	3.0×10^{-5}	3.0×10^{-5}	9.8×10^{-3}	9.8×10^{-3}
	BBP	Algae	6.2×10^{3}	7.2×10^{3}	2.2×10^{3}	3.8×10^{3}
		Crustaceans	5.0×10^{2}	5.8×10^{2}	4.7×10^{2}	8.1×10^{2}
		Fish	1.1×10^{3}	1.3×10^{3}	3.2×10^{3}	5.5×10^{3}
Atlas Cove	DMP	Algae	NA	NA	1.9×10^{-3}	3.8×10^{-3}
		Crustaceans	NA	NA	2.0×10^{-3}	4.0×10^{-3}
		Fish	NA	NA	1.7×10^{-3}	3.4×10^{-3}
	DEP	Algae	6.2×10^{-6}	6.2×10^{-6}	2.0×10^{-3}	2.0×10^{-3}
		Crustaceans	1.85×10^{-5}	1.85×10^{-5}	6.0×10^{-3}	6.0×10^{-3}
		Fish	3.0×10^{-5}	3.0×10^{-5}	9.8×10^{-3}	9.8×10^{-3}
	BBP	Algae	6.5×10^{3}	1.1×10^{4}	1.1×10^{3}	1.32×10^{3}
		Crustaceans	5.4×10^{2}	8.7×10^{2}	2.2×10^{2}	2.9×10^{2}
		Fish	1.2×10^{3}	1.9×10^{3}	1.48×10^{3}	1.93×10^{3}
		RQmix Algae	2.64×10^{4}	3.77×10^{4}	6.55×10^{3}	1.30×10^{4}
		RQmix Crustacean	2.14×10^{3}	3.06×10^{3}	1.40×10^{3}	2.07×10^{3}
		RQmix Fish	4.66×10^{3}	6.66×10^{3}	9.59×10^{3}	1.41×10^{4}

imperative to mitigate the ecological risks posed by these emerging contaminants.

4 Conclusion

The measured physical and chemical parameters met the acceptable criteria, except dissolved oxygen, turbidity, and pH level. The concentrations of PAEs and PBDEs congeners were comparable to previously reported concentrations from Lagos Lagoon. The observed concentrations could be attributed to indiscriminate waste disposal from domestic and industrial activities and urban runoff. PBDEs were detected in all environmental matrices while only BBP and DSBP were detected in both surface water and sediments. The congener profile of PAEs and PBDEs revealed BBP and BDE-153 were in both surface water and sediment. PCA revealed predominance of DMP and high-brominated PBDEs linked to domestic effluents, urban runoff, plastic based materials, and consumer products indicating intense human activities especially at Makoko and Atlas Cove. The RQ for PAEs suggest low risk (RQ < 1) for DEP and DMP, whereas the levels of BBP suggest the potential for significant

ecological risk (RQ > 100), from surface water and sediment at most sampling locations particularly on algae. PBDEs congeners revealed significantly high risks RQs (≥ 100) with hepta-BDE and hexa-BDE exhibiting greatest risks in surface water and sediment at Atlas Cove and Makoko, respectively.

5 Data availability statement

The data will be made available upon request from the corresponding author.

6 Ethical statements

This study does not involve human or animal subjects. Ethical approval was not required for this research.

7 Conflict of interest

The authors declare that there is no conflict of interest.

8 Author contributions

A. I. Obiakara-Amaechi: Conceptualization, methodology, writing – original draft, and writing – review and editing. A. A. Abayomi: Supervision, methodology, and writing – review and editing. L. O. Ipadeola: Formal analysis, data curation, methodology, validation, software, visualization, and writing – review and editing. L. D. Dhikrullah: Investigation, methodology, validation, and writing – review and editing. O. B. Oguntowo: Formal analysis, and writing – review & editing. L. O. Chukwu: Supervision, and writing – review & editing. All authors approved the final version of the manuscript.

9 Copyright statement

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